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Experimental evaluation of the elastic buckling and compressive capacity of laced columns

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ABSTRACT

To investigate the static behavior of laced columns, 18 tests were conducted on sample columns constructed from pairs of u-section profiles with various lengths and various distances between the main chords, all with an initial imperfection. To study the behavior of built-up columns in the plane parallel to the lacing planes, the test set-up was arranged in such a way that buckling occurred in this plane. There was generally good agreement between the test results and the theoretical results for the elastic critical loads. The SSRC method overestimated the results with a high error, whereas Engesser's method was more conservative, with a minor error. Bleich's method and Paul's method both led to results with moderate error. The compressive capacity of the sample columns, obtained by the tests, were compared to those obtained by the Ayrton–Perry and capacity curves methods, of which the first gave conservative results and the second led to the results being slightly overestimated. The experimental results showed that the amount of initial imperfection has a significant effect on reducing the compressive capacity of the samples.

1. Introduction

The behavior of built-up columns is different from solid columns due to the effect of shear deformations. The effect of shear deformations on the elastic critical load of columns was studied for the first time by Engesser [1], who used the modified slenderness method to consider this effect. Bleich [2], Timoshenko and Gere [3] and several other researchers [4–14] also studied the effect of shear deformations on the elastic critical load of built-up columns, either theoretically or experimentally. The effect of using end plates on the critical load of built-up columns was first studied by Lin et al. [15] and Johnston [16]. Further investigation on the end plate effect was then followed by Gjelsvic [17] and Paul [18]. In Lin's method (suggested also by the SSRC guidelines [19]) and Paul's method, the amount of critical load when there are end plates can be obtained through a graph by calculating the parameters that express the specifications of the built-up columns. Most of the building codes, however, use the equivalent slenderness method to account for the shear effects.

Compound buckling is also a factor that affects the elastic critical load of columns. This effect was studied by Duan et al. [20]. However, in laced columns, because of the low values of slenderness of the main chords between the lacing plates compared with the overall slenderness of the built-up column, compound buckling cannot occur.

With regard to the existing complications in calculating the exact elastic critical load of built-up columns by analytical methods, all of the proposed theoretical methods contain simple assumptions, and therefore, it is necessary to evaluate the precision of the different methods by experimental studies. Very few tests have been conducted on built-up columns. Hosseini Hashemi and Jafari [21,22] have investigated the elastic critical load and compressive capacity of batten columns through laboratory tests and have assessed the precision level of the theoretical formulas. However, such tests have not been reported for laced columns.

Another issue, which was evaluated in this study, is the effect of the initial geometric imperfection on the compressive capacity of sample columns. In general, an initial geometrical imperfection can drastically reduce the compressive capacity of built-up and solid columns. Theoretical studies on the effect of initial geometrical imperfections on the strength of built-up columns have been conducted by several researchers [23,24]. All building codes include the effect of initial geometrical imperfections in their design provisions, either directly in their formulas, such as in the British Standard [25], Eurocode3 [26] and AISC-LRFD [27], or indirectly in their suggested safety factor, such as AISC-ASD [28]. Hosseini Hashemi [29] has compared the inclusion of the initial imperfection effect in the compressive capacity of columns in several well-known codes and has concluded that this effect can be significant and should be considered explicitly in the design formulas. This effect can be more significant, particularly in built-up columns, due to their construction and installation process. The most well-known theoretical formula for direct consideration of the initial imperfection effect in the compressive

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capacity of columns is the Ayrton-Perry formula [30], which is used in the British Standard [25] and Eurocode3 [26]. This formula gives a lower bound solution for the column's compressive capacity.

In the first part of this study, several scaled samples of laced built-up columns with different lengths and different spaces between the main chords were tested, and the results for the elastic critical load are compared with those from the theoretical methods of Engesser, Bleich, Paul and SSRC. Then, the compressive capacities, obtained by the tests, are compared with those obtained by the Ayrton–Perry formula, as the lower bound solution, and those obtained by the capacity curves method, as the upper bound solution.

2. Modified Southwell plot for built-up columns

The only method that calculates the elastic critical load of columns using experimental data is the Southwell plot method [31]. Because the conventional Southwell plot does not take into account the effect of shear deformations, it is suitable for only solid columns; thus, it will give erroneous results for built-up columns. Therefore, it should be modified to account for shear deformations. Based on Fig. 1, which shows the general buckled shape of a column, the following steps are proposed to modify the Southwell plot.

a) The governing differential equation of a perfect, doubly pinned column that considers shear deformation is:

$$EI(1-P/k_s)w''(z)+Pw(z)=0 \tag{1}$$

where E, I and k_s are, respectively, the Young modulus, moment of inertia, and shear stiffness of the column cross section, which are assumed constant along the column. The solution in the critical state is:

$$P_{cri}=\frac{P_{ei}}{1+\frac{P_{ei}}{k_s}} \tag{2}$$

where P_{cri} is the elastic critical load in the ith mode and P_{ei} is given by:

$$P_{ei}=EI\left(\frac{i\pi}{L}\right)^2 \tag{3}$$

Assuming $\phi_i(z)$ is the buckling shape of the ith mode of the column, $\phi_i''(z)$ is given by:

$$\phi_i''(z)=-\frac{P_{cri}\phi_i(z)}{EI\left(1-\frac{P_{cri}}{k_s}\right)}=-\left(\frac{i\pi}{L}\right)^2\phi_i(z) \tag{4}$$

b) When the column has an initial imperfection, the governing equation for buckling is:

$$EI(1-P/k_s)\left[w''(z)-w_0''(z)\right]+Pw(z)=0 \tag{5}$$

Expressing the initial curve and the buckled shape in terms of buckling mode shapes in Eq. (5) results in:

$$w_0(z)=\sum_{i=1}^{n}\Delta_{0i}\phi_i(z) \tag{6}$$

$$w(z)=\sum_{i=1}^{n}\delta_i\phi_i(z) \tag{7}$$

$$EI(1-P/k_s)\left[\sum_{i=1}^{n}\delta_i\phi_i''(z)-\sum_{i=1}^{n}\Delta_{0i}\phi_i''(z)\right]+P\sum_{i=1}^{n}\delta_i\phi_i(z)=0 \tag{8}$$

Substituting $\phi_i''(z)$ from Eq. (4) into Eq. (8) gives:

$$-EI(1-P/k_s)\sum_{i=1}^{n}[\delta_i-\Delta_{0i}]\left(\frac{i\pi}{L}\right)^2\phi_i(z)+P\sum_{i=1}^{n}\delta_i\phi_i(z)=0 \tag{9}$$

Regarding the orthogonality of the mode shapes, Eq. (9) results in the following equation for each mode:

$$-EI(1-P/k_s)[\delta_i-\Delta_{0i}]\left(\frac{i\pi}{L}\right)^2\phi_i(z)+P\delta_i\phi_i(z)=0\rightarrow i=1,2,\ldots,n \tag{10}$$

Assuming $\delta_i=\Delta_i+\Delta_{0i}$ and considering Eq. (3), one can write:

$$-(1-P/k_s)\Delta_iP_{ei}+P(\Delta_i+\Delta_{0i})=0 \tag{11}$$

For the first mode of buckling ($i=1$), Eq. (11) can be written as:

$$\Delta_1=P_{e1}\left(\frac{k_s-P}{k_sP}\right)\Delta_1-\Delta_{01} \tag{12}$$

Eq. (12) is similar to Southwell's equation. With the value of the applied axial load, P, with the displacement at the mid-height of the column, Δ_1, and by drawing a line based on Eq. (12), the values of the initial geometrical imperfection, Δ_{01}, and the corresponding buckling load, P_{e1}, are obtained, as shown in Fig. 2.

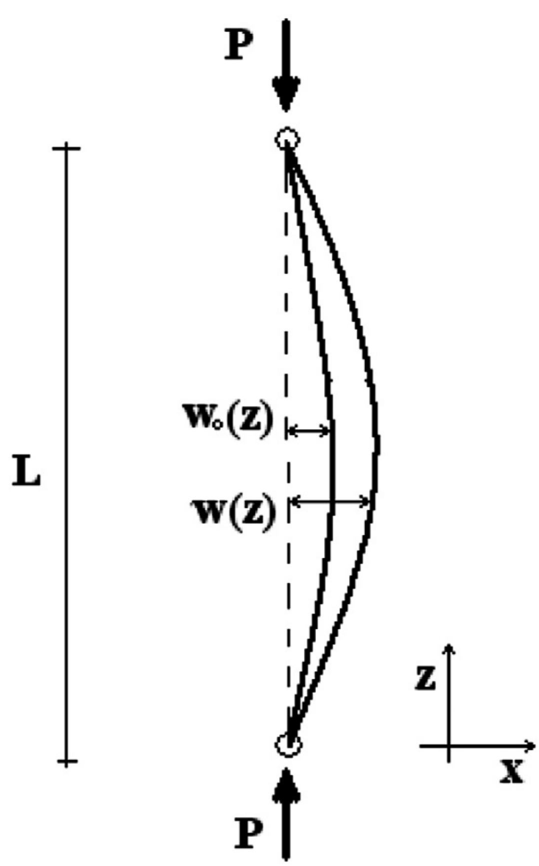

Fig. 1. General buckled shape of a column.